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SPECIFICATION

Heat-resistant, High-toughness Aluminum Alloy, Method of Manufacturing the Same, and Engine Parts

TECHNICAL FIELD

[0001]

The present invention relates to heat-resistant, high-toughness aluminum alloys, methods of manufacturing the same, and engine parts, and particularly to heat-resistant, high-toughness aluminum alloys which are made by rapid solidification and are suitable as materials for automotive engine parts, for which high heat resistance and toughness are required, particularly as materials for pistons.

BACKGROUND ART

[0002]

Unexamined Japanese patent publication 11-293374 (patent publication 1) discloses heat-resistant, rapidly solidified aluminum alloys of Al (aluminum) - Si (silicon) - transition metal. Specifically, this publication discloses aluminum alloys comprising 10 to 30 mass % of Si, 1 to 5 mass % of Ti (titanium), 3 to 10 mass % in total of at least one of Fe (iron) and Ni (nickel), and 0.05 to 1.0 mass % of Mg (magnesium), the balance being essentially Al, and in which the silicon has an average grain diameter of not more than 2 μm, and the intermetallic compound phase not containing Si has an average grain diameter of not more than 1 μm.

[0003]

This publication also discloses that the above aluminum alloys are used for e.g. engine parts.

Patent publication 1: Unexamined Japanese patent publication 11-293374

DISCLOSURE OF THE INVENTION

PROBLEMS TO WHICH THE INVENTION SEEKS A SOLUTION

[0004]

The aluminum alloys disclosed in the above patent publication are suitable as materials for e.g. engine parts because they have high heat resistance and high wear resistance. In cases where higher load operation is required for engines, e.g. for car races, besides high strength, high toughness and low specific gravity, lightness in weight and high durability are also required for engine parts, particularly for pistons. Therefore, the need for materials which satisfy these requirements is increasing.

[0005]

An object of the present invention is to provide heat-resistant, high-toughness aluminum alloys which have a good balance between strength and ductility at a temperature range from room temperature to around 300 degrees C and have high fracture toughness, a method of manufacturing the same, and engine parts made of such alloys.

MEANS TO SOLVE THE PROBLEMS

[0006]

The heat-resistant, high-toughness aluminum alloy according to the present invention comprises not less than 10 mass % and not more than 16 mass % of silicon, not less than 1 mass % and not more than 3 mass % of iron, not less than 1 mass % and not more than 2 mass % of nickel, not less than 0.5 mass % and not more than 2 mass % in total of one or more selected from the group consisting of titanium, zirconium, chromium and

vanadium, not less than 0.6 mass % and not more than 3 mass % of copper, and not less than 0.2 mass % and not more than 2 mass % of magnesium, the balance being essentially aluminum, the alloy being obtained by densifying aluminum alloy powder prepared by gas atomizing, the silicon having an average grain diameter of not more than 4 μm.

[0007]

Preferably, the heat-resistant, high-toughness aluminum alloy contains titanium by not less than 0.5 mass % and not more than 2 mass %.

[0008]

Preferably, the heat-resistant, high-toughness aluminum alloy has a density of 2.8 Mg/m^3 or less.

[0009]

The engine parts according to the present invention are manufactured by subjecting any of the abovementioned heat-resistant, high-toughness aluminum alloys to hot plastic working.

[0010]

The engine parts are preferably pistons.

[0011]

One method of manufacturing a heat-resistant, high-toughness aluminum alloy according to the present invention comprises preparing aluminum alloy powder by gas atomizing, the aluminum alloy powder comprising not less than 10 mass % and not more than 16 mass % of silicon, not less than 1 mass % and not more than 3 mass % of iron, not less than 1 mass % and not more than 2 mass % of nickel, not less than 0.5 mass % and not more than 2 mass % in total of one or more selected from the group consisting of titanium, zirconium, chromium and vanadium, not less than 0.6 mass % and not more than 3 mass % of copper, and not less than 0.2

mass % and not more than 2 mass % of magnesium, the balance being essentially aluminum, subjecting the aluminum alloy powder to cold forming to obtain a preform, heating the preform to a temperature range of not less than 400 degrees C and not more than 510 degrees C and holding the preform in the temperature range for 5 hours or less, and subjecting the preform to hot plastic working to densify the preform, thereby obtaining a dense body as the heat-resistant, high-toughness aluminum alloy, the silicon in the aluminum alloy having an average grain diameter of 4μm or less.

[0012]

Another method of manufacturing a heat-resistant, high-toughness aluminum alloy according to the present invention comprises preparing aluminum alloy powder by gas atomizing, the aluminum alloy powder comprising not less than 10 mass % and not more than 16 mass % of silicon, not less than 1 mass % and not more than 3 mass % of iron, not less than 1 mass % and not more than 2 mass % of nickel, not less than 0.5 mass % and not more than 2 mass % in total of one or more selected from the group consisting of titanium, zirconium, chromium and vanadium, not less than 0.6 mass % and not more than 3 mass % of copper, and not less than 0.2 mass % and not more than 2 mass % of magnesium, the balance being essentially aluminum, subjecting the aluminum alloy powder to cold forming to obtain a preform, heating the preform to a temperature range of 400 degrees C to 510 degrees C and holding the preform in the temperature range for 5 hours or less, subjecting the preform to hot plastic working to densify the preform, thereby obtaining a dense body, and subjecting the dense body to hot plastic working by heating to a temperature not higher than the heating temperature of the preform, thereby manufacturing the

aluminum alloy, the silicon in the aluminum alloy having an average grain diameter of 4 μm or less.

[0013]

In either of the above methods, the step of subjecting the heated preform to hot plastic working preferably includes extrusion with an extrusion ratio of 6 or more.

ADVANTAGES OF THE INVENTION

[0014]

The present inventors have discovered that by preparing aluminum alloy powder of a predetermined composition by gas atomizing and densifying the aluminum alloy powder thus prepared, heat-resistant, high-toughness aluminum alloys can be obtained which have a good balance between strength and ductility at a temperature range from room temperature to around 300 degrees C and have high fracture toughness. Such aluminum alloys are suitable as materials for automotive engines parts such as pistons.

[0015]

In the heat-resistant, high-toughness aluminum alloy according to the present invention, silicon is important to improve heat resistance while keeping a low specific gravity. The content of silicon should be not less than 10 mass % and not more than 16 mass % because if the silicon content is less than 10 mass %, the strength at high temperature tends to be low. If over 16 mass %, the elongation and impact value at high temperature tend to be low.

[0016]

Iron is important to improve heat resistance. The content of iron

should be not less than 1 mass % and not more than 3 mass % because if the iron content is less than 1 mass %, the strength at high temperature will be low. If over 3 mass %, the elongation and the impact value at high temperature will be low.

[0017]

Nickel is important to improve heat resistance. The content of nickel should be not less than 1 mass % and not more than 2 mass % because if the nickel content is less than 1 mass %, the strength at high temperature tends to be low. If over 2 mass %, the elongation and the impact value at high temperature will be low.

[0018]

One or more of titanium, zirconium, chromium and vanadium is important for densification of the material and to improve the strength by forming an intermetallic compound with aluminum and functioning as a core of crystal formation. The total content of such one or more of titanium, zirconium, chromium and vanadium should be not less than 0.5 mass % and not more than 2 mass % because if it is less than 0.5 mass %, the strength at high temperature and the strength at room temperature will be low, and if over 2 mass %, the elongation and the impact value at high temperature will be low.

[0019]

Copper is important to improve the strength by ageing precipitation hardening at a temperature range from room temperature to around 200 degrees C. The content of copper should be not less than 0.6 mass % and not more than 3 mass % because if the copper content is less than 0.6 mass %, the strength at high temperature and the strength at room temperature will, and if over 3 mass %, the impact value decreases and the density

increases.

[0020]

Magnesium has an effect similar to copper. The content of magnesium should be not less than 0.2 mass % and not more than 2 mass % because if the magnesium content is less than 0.2 mass %, the strength at room temperature is low, and if over 2 mass %, the impact value and the elongation at room temperature decrease.

[0021]

Since the heat-resistant, high-toughness aluminum alloys contain titanium, which has a low specific gravity, in the amount of not less than 0.5 mass % and not more than 2 mass %, their specific gravity decreases, and their properties further improve.

[0022]

By setting the density of the heat-resistant, high-toughness aluminum alloys below 2.8 Mg/m^3, it is possible to reduce their specific gravity and thus reduce the weight of parts made therefrom.

[0023]

Because the engine parts according to the present invention are manufactured by subjecting any of the abovementioned heat-resistant, high-toughness aluminum alloys to hot plastic working, they satisfy the requirements for strength, toughness and low specific gravity and are lightweight and have excellent durability.

[0024]

By either of the methods of manufacturing heat-resistant, high-toughness aluminum alloys according to the present invention, it is possible to manufacture heat-resistant, high-toughness aluminum alloys which have a good balance between strength and ductility at a temperature

range from room temperature to around 300 degrees C and have high fracture toughness. The dense body is subjected to hot plastic working by heating at a temperature lower than the temperature for heating the preform. It is to prevent the ductility from decreasing.

[0025]

In the methods of manufacturing heat-resistant, high-toughness aluminum alloys according to the present invention, extrusion is carried out with the extrusion ratio of 6 or more to improve toughness.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026]

Fig. 1 is a flow chart showing a first method of manufacturing the heat-resistant, high-toughness aluminum alloy embodying the present invention;

Fig. 2 is a flow chart showing a second method of manufacturing the heat-resistant, high-toughness aluminum alloy embodying the present invention;

Fig. 3 is a front view of a tensile test specimen;

Fig. 4(a) is a front view of an impact test specimen;

Fig. 4(b) is a sectional view of the same; and

Fig. 4(c) is an enlarged view of a notch.

DESCRIPTION OF NUMERALS

[0027]

1 Tensile test specimen

2 Impact test specimen

2a Notch

BEST MODE FOR EMBODYING THE INVENTION

[0028]

Now the embodiments of the present invention are described with reference to the drawings.

[0029]

A heat-resistant, high-toughness aluminum alloy embodying the present invention comprises not less than 10 mass % and not more than 16 mass % of silicon, not less than 1 mass % and not more than 3 mass % of iron, not less than 1 mass % and not more than 2 mass % of nickel, not less than 0.5 mass % and not more than 2 mass % in total of one or more of titanium, zirconium, chromium and vanadium, not less than 0.6 mass % and not more than 3 mass % of copper and not less than 0.2 mass % and not more than 2 mass % of magnesium, the balance being essentially aluminum. The heat-resistant, high-toughness aluminum alloy of this embodiment is obtained by densifying aluminum alloy powder prepared by gas atomizing. The silicon therein has an average grain diameter of not more than 4 μm.

[0030]

Preferably, the heat-resistant, high-toughness aluminum alloy according to the present invention contains titanium in the amount of not less than 0.5 mass % and not more than 2 mass %. Also, the heat-resistant, high-toughness aluminum alloy of this invention preferably has a density of 2.8 Mg/m^3 or less.

[0031]

Pistons are manufactured by subjecting the heat-resistant, high-toughness aluminum alloy of this invention to hot plastic working.

[0032]

Next, the methods of manufacturing the heat-resistant high-toughness aluminum alloy embodying this invention are described.

[0033]

Fig. 1 is a flow chart showing a first method of manufacturing a heat-resistant, high-toughness aluminum alloy embodying the present invention. As shown in Fig. 1, a predetermined molten composition is prepared (Step 1) which comprises not less than 10 mass % and not more than 16 mass % of silicon, not less than 1 mass % and not more than 3 mass % of iron, not less than 1 mass % and not more than 2 mass % of nickel, and not less than 0.5 mass % and not more than 2 mass % in total of one or more of titanium, zirconium, chromium and vanadium, the balance being essentially aluminum. Preferably, the molten composition contains titanium in the amount of not less than 0.5 mass % and not more than 2 mass %.

[0034]

The molten composition is air atomized to prepare aluminum alloy powder (Step S2). The aluminum alloy powder is then cold compression molded into a preform (Step S3). The preform is heated to a temperature of not lower than 400 degrees C and not higher than 510 degrees C and maintained in this temperature range for 5 hours or less in an atmospheric furnace (Step S4). The heated preform is densified by hot plastic working into a dense body (Step S5). The hot plastic working is preferably extrusion with the extrusion ratio of 6 or more. The dense body is then cut and heated to a temperature lower than the heating temperature of the preform (not lower than 400℃ and not higher than 510℃) and subjected to hot plastic working (Step S6). The heat-resistant, high-toughness aluminum alloy of this embodiment is thus obtained, the silicon therein

having an average grain diameter of not more than 4 μm.

[0035]

The aluminum alloy thus produced is worked into test specimens (Step S7) which are subjected to material tests (tensile test and Charpy impact test), to be described below (Step S8).

[0036]

Fig. 2 is a flow chart showing the second method of manufacturing a heat-resistant, high-toughness aluminum alloy embodying the present invention. As shown in Fig. 2, this method is the same as the method of Fig. 1 from Step S1 to Step S5. After Step S5, the dense body densified by extrusion is cut (Step S11), heated (Step S12), subjected to plastic working (swaging) (Step S13) and subjected to heat treatment (Step S14).

[0037]

Thereafter, in this method, too, as in the method of Fig. 1, the aluminum alloy is worked into test specimens (Step S7), which are subjected to material tests (tensile test and Charpy impact test), to be described below (Step S8).

EXAMPLE 1

[0038]

Examples of the present invention are now described.

[0039]

Molten compositions shown in Table 1 were prepared and formed into tensile test specimens and impact test specimens according to the flow of Fig. 1. Figs. 3 and 4 show a tensile test specimen and an impact test specimen, respectively. Fig. 3 is a front view of the tensile test specimen 1. Fig. 4(a) is a front view of the impact test specimen 2, Fig. 4(b) is its

sectional view, and Fig. 4(c) is its enlarged view showing its notch 2a.

[0040]

For these test specimens, measurements were made of the average grain diameter of the silicon, tensile strength and elongation at 300 degrees C, tensile strength and elongation at room temperature (20 degrees C), impact value and density. Table 2 shows the results. Table 2 also shows the solidifying temperature of the preform formed into the respective test specimens, holding time after heating the preform, and extrusion ratio, solution treatment temperature, and artificial ageing temperature for the heated preform.

[0041]

[Table 1]

	Specimen No.	Content (mass%)								
		Si	Fe	Ni	Ti	Cr	Zr	V	Cu	Mg
Example of the invention	1	10	2	1.3	1.1	–	–	–	1	0.5
	2	12	2.1	1.6	1.2	–	–	–	0.9	0.7
	3	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	4	15	1.9	1.5	1.6	–	–	–	1.3	0.6
	5	16	2.1	1.4	1.4	–	–	–	1.4	0.8
	6	13	1.1	2.1	1	–	–	–	1.5	1
	7	13	2.8	1.1	1.5	–	–	–	1.4	0.6
	8	13	2.1	1.1	1.3	–	–	–	1.3	1
	9	13	1.2	2.9	1.2	–	–	–	1	1.1
	10	13	2	1.4	0.5	–	–	–	1.1	0.5
	11	13	1.8	1.3	1.8	–	–	–	0.9	0.8
	12	13	1.8	1.5	–	1.2	–	–	0.8	0.6
	13	13	1.9	1.6	–	–	–	1.3	1.1	0.5
	14	13	1.8	1.4	–	–	1.2	–	1	0.8
	15	13	1.9	1.5	1.1	–	–	–	0.6	0.9
	16	13	2	1.3	1	–	–	–	2.8	1
	17	13	1.8	1.5	1	–	–	–	0.9	0.4
	18	13	2.1	1.6	1.3	–	–	–	1.1	1.5
Comparative Example	19	8	2.3	1.6	0.9	–	–	–	1.1	0.5
	20	18	2	1.5	1.2	–	–	–	1.4	0.6
	21	13	4	–	1	–	–	–	1.2	0.8
	22	13	–	4.2	1.1	–	–	–	1.1	0.7
	23	13	3	2.8	0.8	–	–	–	1	1
	24	13	0.8	0.5	0.8	–	–	–	1.2	0.8
	25	13	2.2	1.4	2.2	–	–	–	1	1
	26	13	2.1	1.3	0.2	–	–	–	1	0.9
	27	13	2.1	1.4	1.1	–	–	–	3.5	0.7
	28	13	2.1	1.5	1	–	–	–	0.2	0.8
	29	13	2	1.3	0.9	–	–	–	0.9	2.5
	30	13	2.4	1.5	0.9	–	–	–	0.8	0.1

[0042]

[Table 2]

	Specimen No.	Solidifying temp. (℃)	Holding time after heating (min)	Extrusion ratio	Solution treatment temp. (℃)	Artificial ageing temp. (℃)	Grain size of Si (μm)	Tensile strength at 300℃ (MPa)	Elongation at 300℃ (%)	Tensile strength at 20℃ (MPa)	Elongation at 20℃ (%)	Impact value (J/cm²)	Density (Mg/m³)
Example of the invention	1	480	60	8	470	200	1.9	105	35	390	10.0	4.5	2.75
	2	480	60	8	470	200	2.2	110	31	400	9.5	3.9	2.74
	3	480	60	8	470	200	1.7	120	30	410	6.0	2.7	2.74
	4	480	60	8	470	200	1.8	128	28	420	5.5	2.4	2.73
	5	480	60	8	470	200	2.5	135	20	432	3.5	2.3	2.72
	6	480	60	8	470	200	1.7	105	33	402	5.0	3.8	2.71
	7	480	60	8	470	200	1.8	130	28	423	3.7	2.2	2.76
	8	480	60	8	470	200	2.2	115	31	410	4.1	3.1	2.74
	9	480	60	8	470	200	2.1	125	29	435	3.5	2.1	2.74
	10	480	60	8	470	200	2.3	121	31	400	4.5	3.6	2.73
	11	480	60	8	470	200	2.6	135	25	441	3.4	2.2	2.72
	12	480	60	8	470	200	2.1	131	30	450	3.1	2.5	2.74
	13	480	60	8	470	200	2.0	125	27	443	3.3	2.4	2.75
	14	480	60	8	470	200	2.1	130	28	440	3.5	2.6	2.73
	15	480	60	8	470	200	2.2	110	33	410	7.2	3.1	2.68
	16	480	60	8	470	200	1.8	115	29	430	4.5	2.2	2.79
	17	480	60	8	470	200	1.7	118	31	405	7.0	3.1	2.74
	18	480	60	8	470	200	2.1	120	35	440	3.1	2.1	2.72
Comparative Example	19	480	60	8	470	200	1.8	65	40	370	13.0	4.9	2.78
	20	480	60	8	470	200	2.8	170	15	390	2.4	1.8	2.72
	21	480	60	8	470	200	2.1	110	16	430	2.8	1.8	2.75
	22	480	60	8	470	200	2.3	100	15	440	1.8	1.7	2.75
	23	480	60	8	470	200	2.1	180	12	460	1.9	1.2	2.77
	24	480	60	8	470	200	2.0	70	32	380	9.1	5.2	2.70
	25	480	60	8	470	200	2.5	135	15	470	1.8	1.5	2.75
	26	480	60	8	470	200	1.8	80	35	370	5.5	3.5	2.71
	27	480	60	8	470	200	1.9	110	29	430	3.0	2	2.80
	28	480	60	8	470	200	2.3	90	36	380	5.0	3.6	2.70
	29	480	60	8	470	200	2.2	110	38	460	1.0	0.8	2.70
	30	480	60	8	470	200	2.4	105	29	370	7.0	3	2.75

[0043]

The results in Tables 1 and 2 for Examples No. 1 to No. 5 of the

invention and Comparative Examples No. 19 and No. 20 show that by adjusting the content of silicon to not less than 10 mass % and not more than 16 mass %, the material revealed strength and toughness in a balanced manner. Where the content of silicon was over 16 mass %, ductility was not good (Comparative Example No. 20). Where the silicon content was less than 10 mass %, the strength decreased (Comparative Example No. 19).

[0044]

The results for Examples No. 6 to No. 9 and Comparative Examples No. 21 to No. 24 show that by adjusting the contents of Fe and Ni to ranges of not less than 1 mass % and not more than 3 mass % and not less than 1 mass % and not more than 2 mass %, respectively, the material revealed strength and toughness in a balanced manner. When the Fe content alone or the Ni content alone is increased above the above range in an attempt to improve the heat resistance, coarse intermetallic compounds deposited, thus impairing toughness (Comparative Examples No. 21 and No. 22). When their contents were below the above ranges, heat resistance was impaired. When the material contained both Fe and Ni, if their contents were over the respective ranges, coarse intermetallic compounds deposited, thus impairing toughness (Comparative Example No. 23). When their contents were below the respective ranges, the heat resistance was impaired (Comparative Example No. 24).

[0045]

The results for Examples No. 10 to No. 14 of the invention and Comparative Examples No. 25 and No. 26 show that by adjusting the content of Ti to not less than 0.5 mass % and not more than 2 mass %, the material revealed strength and toughness in a balanced manner. Similar

effects were obtained by adding Zr, Cr, or V in place of Ti. When the total content of these components (Ti, Zr, Cr, V) was over 2 mass %, toughness was impaired (Comparative Example No. 25). When it was less than 0.5 mass %, the strength decreased (Comparative Example No. 26).

[0046]

The results for Examples No. 15 and No. 16 of the invention and Comparative Examples No. 27 and No. 28 show that by adjusting the content of Cu to not less than 0.6 mass % and not more than 3 mass %, the material revealed strength and toughness in a balanced manner. When the content of Cu was over 3 mass %, the density unduly increased (Comparative Example No. 27), and when it was less than 0.6 mass %, the strength decreased (Comparative Example No. 28).

[0047]

The results for Examples No. 17 and No. 18 of the invention and Comparative Examples No. 29 and No. 30 show that by adjusting the content of Mg to not less than 0.2 mass % and not more than 2 mass %, the material revealed strength and toughness in a balanced manner. When the content of Mg was over 2 mass %, the toughness decreased (Comparative Example No. 29), and when it was less than 0.2 mass %, the strength decreased (Comparative Example No. 30).

EXAMPLE 2

[0048]

It was checked how the heating conditions during densification affect the characteristics.

[0049]

Molten compositions shown in Table 3 were prepared and formed

into tensile test specimens and impact test specimens according to the flow of Fig. 1. Figs. 3 and 4 show a tensile test specimen and an impact test specimen, respectively.

[0050]

For these test specimens, measurements were made of the average grain diameter of the silicon, tensile strength and elongation at 300 degrees C, tensile strength and elongation at room temperature (20 degrees C), impact value and density. Table 4 shows the results. Table 4 also shows the solidifying temperature of the preform formed into the respective test specimens, holding time after heating the preform, and extrusion ratio, solution treatment temperature, and artificial ageing temperature for the heated preform.

[0051]

[Table 3]

	Specimen No.	Content (mass%)								
		Si	Fe	Ni	Ti	Cr	Zr	V	Cu	Mg
Example of the invention	31	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	32	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	33	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	34	13	2.1	1.4	0.9	–	–	–	1.1	0.7
Comparative Example	35	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	36	13	2.1	1.4	0.9	–	–	–	1.1	0.7
Example of the invention	37	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	34	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	38	13	2.1	1.4	0.9	–	–	–	1.1	0.7
Comparative Example	39	13	2.1	1.4	0.9	–	–	–	1.1	0.7

[0052]

[Table 4]

	Specimen No.	Solidifying temp. (°C)	Holding time after heating (min)	Extrusion ratio	Solution treatment temp. (°C)	Artificial ageing temp. (°C)	Grain size of Si (μm)	Tensile strength at 300°C (MPa)	Elongation at 300°C (%)	Tensile strength at 20°C (MPa)	Elongation at 20°C (%)	Impact value (J/cm²)	Density (Mg/m³)
(1)	31	400	60	8	390	200	1.5	145	22	420	3.5	2.5	2.74
	32	430	60	8	420	200	1.5	130	28	411	4.5	2.7	2.74
	33	480	60	8	470	200	1.7	120	30	410	6.0	2.7	2.74
	34	510	60	8	500	200	2.5	115	33	403	6.5	3.4	2.74
(2)	35	530	60	8	520	200	4.5	105	20	360	2.4	2.0	2.74
	36	380	60	8	370	200	1.4	148	19	430	2.1	1.7	2.74
(1)	37	510	30	8	500	200	1.9	120	32	420	5.7	2.8	2.74
	34	510	180	8	500	200	2.5	115	33	403	6.5	3.4	2.74
	38	510	270	8	500	200	2.8	100	36	380	6.6	3	2.74
(2)	39	510	330	8	500	200	3.3	85	30	360	4.1	2.5	2.74

(1) Example of the invention
(2) Comparative Example

[0053]

The results in Tables 3 and 4 for Examples No. 31 to No. 34 of the invention and Comparative Examples No. 35 and No. 36 show that by setting the heating and holding temperature of the preform in the solidifying step to a range of 400 degrees C to 510 degrees C, the material revealed strength and toughness in a balanced manner. When the solidifying temperature was higher than 510 degrees C, not only strength decreased but also the silicon crystals became coarse and functioned as a source of stress concentration, so that ductility decreased (Comparative Example No. 35). When the solidifying temperature was lower than 400 degrees C, strength increased, but toughness was impaired (Comparative Example No. 36).

[0054]

The results for Examples No. 37 and No. 38 and Comparative Example No. 39 show that by setting the holding time after heating to solidify the preform to not longer than 5 hours, it was possible to prevent the decrease of strength and the decrease of ductility due to coarsening of silicon crystals. When the holding time after heating was longer than 5 hours, both strength and ductility decreased (Comparative Example No. 39).

EXAMPLE 3

[0055]

The effects of the plastic working method in densification have been examined.

[0056]

Molten compositions shown in Table 5 were prepared and formed into tensile test specimens and impact test specimens according to the flow of Fig. 1. Figs. 3 and 4 show a tensile test specimen and an impact test specimen, respectively.

[0057]

For the test specimens thus prepared, measurements were made of the average grain diameter of the silicon therein, tensile strength and elongation at 300 degrees C, tensile strength and elongation at room temperature (20 degrees C), impact value and density. Table 6 shows the results. Table 6 also shows the solidifying temperature for the perform in preparing the test specimens, holding time after heating the preform, and extrusion ratio, solution treatment temperature and artificial ageing temperature for the heated preform.

[0058]

[Table 5]

	Specimen No.	Content (mass%)								
		Si	Fe	Ni	Ti	Cr	Zr	V	Cu	Mg
Example of the invention	40	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	41	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	42	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	43	13	2.1	1.4	0.9	–	–	–	1.1	0.7
Comparative Example	44	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	45	13	2.1	1.4	0.9	–	–	–	1.1	0.7

[0059]

[Table 6]

	Specimen No.	Solidifying temp. (°C)	Holding time after heating (min)	Extrusion ratio	Solution treatment temp. (°C)	Artificial ageing temp. (°C)	Grain size of Si (μm)	Tensile strength at 300°C (MPa)	Elongation at 300°C (%)	Tensile strength at 20°C (MPa)	Elongation at 20°C (%)	Impact value (J/cm²)	Density (Mg/m³)
(1)	40	480	60	6	470	200	1.5	145	30	420	4.5	2.5	2.74
	41	480	60	8	470	200	1.5	142	32	425	4.5	2.7	2.74
	42	480	60	10	470	200	1.7	144	32	430	5.0	2.7	2.74
	43	480	60	12	470	200	1.8	140	35	425	6.5	2.8	2.74
(2)	44	480	60	2	470	200	2.0	105	6	360	0.8	0.5	2.73
	45	480	60	4	470	200	1.5	110	8	370	0.9	0.6	2.74

(1) Example of the invention
(2) Comparative Example

[0060]

The results in Tables 5 and 6 for Examples No. 40 to No. 43 of the invention and Comparative Examples Nos. 44 and 45 show that when extrusion is used in the densifying step, by setting the extrusion ratio to not less than 6, the material revealed strength and toughness in a balanced manner. When the extrusion ratio was less than 6, the toughness decreased

remarkably (Comparative Examples Nos. 44 and 45).

EXAMPLE 4

[0061]

The material of Example No. 4 of the invention prepared in Example 1 was subjected to hot plastic working according to the flow of Fig. 2. From the material thus prepared, specimens of shapes shown in Figs. 3 and 4 were cut out and evaluated to determine their characteristics. The manufacturing conditions and the results of evaluation are shown in Tables 7 and 8.

[0062]

[Table 7]

	Specimen No.	Content (mass%)								
		Si	Fe	Ni	Ti	Cr	Zr	V	Cu	Mg
Example of the invention	46	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	47	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	48	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	49	13	2.1	1.4	0.9	–	–	–	1.1	0.7
Comparative Example	50	13	2.1	1.4	0.9	–	–	–	1.1	0.7
	51	13	2.1	1.4	0.9	–	–	–	1.1	0.7

[0063]

[Table 8]

	Specimen No.	Solidifying temp. (°C)	Holding time after heating (min)	Extrusion ratio	Heating temp. of extruded moterial (°C)	Solution treatment temp. (°C)	Artificial ageing temp. (°C)	Grain size of Si (μm)	Tensile strength at 300°C (MPa)	Elongation at 300°C (%)	Tensile strength at 20°C (MPa)	Elongation at 20°C (%)	Impact value (J/cm²)	Density (Mg/m³)
(1)	46	480	60	8	400	470	200	1.8	145	35	420	5.0	3	2.74
	47	480	60	8	450	470	200	1.9	142	38	425	5.5	3.5	2.74
	48	480	60	8	460	470	200	1.8	141	40	422	6.0	3.3	2.74
	49	480	60	8	480	470	200	2.0	135	42	420	6.5	3.2	2.74
(2)	50	480	60	8	500	490	200	4.5	95	25	380	4.0	2.8	2.74
	51	480	60	8	520	500	200	6.4	90	18	370	3.0	2	2.74

(1) Example of the invention
(2) Comparative Example

[0064]

The results for Examples No. 46 to No. 49 of the invention and Comparative examples Nos. 50 and 51 show that among the characteristics of the materials obtained by hot plastic working at a higher temperature than the solidifying temperature for the extruded material, both strength and ductility decreased (comparative examples Nos. 50 and 51).

[0065]

All the embodiments and examples disclosed herein should be considered to be not restrictive but exemplary in all respects. The scope of the present invention should be defined not by the above description but by the claims and includes all and any modifications falling in the meanings and scope of the claims.

INDUSTRIAL APPLICABILITY

[0066] The heat-resistant, high-toughness aluminum alloys according to the present invention are advantageously used as materials for automotive engine parts for which heat resistance and toughness are required, particularly as materials for pistons.